

# MARS PATHFINDER MICROROVER, IMPLEMENTING A LOW COST PLANETARY MISSION EXPERIMENT

IAA 1-0510

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## ABSTRACT

The **Mars Pathfinder Microrover Flight Experiment (MFEX)** is a **NASA Office of Space Access and Technology (OSAT)** flight experiment which has been delivered and integrated **with** the Mars Pathfinder (MPF) Lander and spacecraft system. The **total cost of the MFEX mission**, including all subsystem design and development, test, **integration with** the MPF lander and operation on Mars has been capped at \$25M. **At time of delivery**, approximately two-thirds of the cost has been incurred. The components of **this rover**, implemented in combinations of commercial, mil-spec and some space **qualified** parts, **have** undergone and passed env. 1111111,111 and operational test series derived from that expected in configuration with the lander and in operation on the **Martian surface**.

**This** paper discusses **the** process and the implementation scheme which has resulted in the development of this first Mars rover. **The** subsystem designs which have proven **successful (and not so successful)** are also described briefly along with the requirements and **constraints (with cost as an integral factor)** which resulted in these designs. **The** qualification **status** of **these** subsystems is also presented.

## INTRODUCTION

On **July 4, 1997** the **Mars Pathfinder (MPF)** spacecraft enters the **Martian** atmosphere, is braked **successively** by an aeroshell parachute, rockets and airbags. **Once** on the surface the lander (**the remaining portion of the spacecraft**) rights itself by **retracting** airbags and deploying **petals**. On the petals are solar panels which will power the lander for the remainder of its mission. On one of these petals is the Microrover Flight Experiment (MFEX), the first roving vehicle on Mars.

The MFEX is a flight experiment of autonomous, mobile vehicle technologies, whose primary mission is to determine microrover performance in the poorly understood planetary terrain of **Mars**. After landing, the microrover is deployed from the lander and begins a nominal 7 sol (1 sol = 1 Martian day) mission to conduct a technology experiments as determining wheel-soil interactions, navigating, traversing and

avoiding hazards, and gathering **data which** characterizes the engineering **capability of the** vehicle (thermal control, power generation performance, communication, etc.). In addition, the microrover carries an **alpha proton x-ray spectrometer (APXS)** which when deployed on rocks and soil **will** determine element composition. Lastly, to enhance the engineering **data return of** the MPF mission, the microrover will image **the** lander to assist in status/damage assessment<sup>1</sup>.

## DESCRIPTION

The MFEX rover (see Fig. 1) is a 10.5kg, 6-wheeled vehicle 60cm x 48cm x 30cm in size. A rocker bogie design is employed which **allows** the traverse of obstacles a wheel diameter (13cm) in size. Each wheel has **cleats** and is independently actuated and geared **providing the** capability of climbing in soft sand and scrambling over rocks. **The front and rear wheels** are independently steered, providing the

capability for the vehicle to turn in place (74cm turning diameter). The vehicle has a top speed of 0.4m/min.

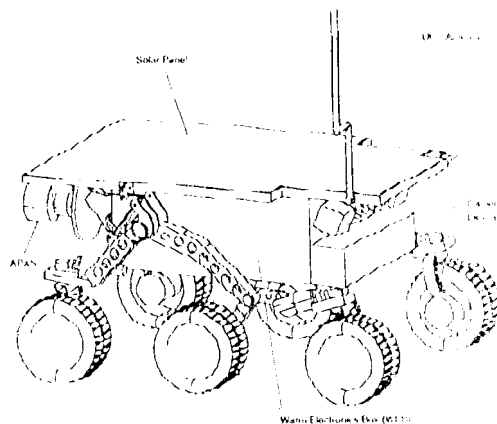


Fig. 1 MFEX microrover

The rover is powered by a 0.22sqm solar panel providing 16W of peak power. The solar panel is backed up by primary batteries, providing up to 150W-hr of energy. The normal driving power requirement for the microrover is 10W.

Rover components not designed to survive ambient Mars temperatures (-110degC during a Martian night) are contained in the warm electronics box (WEB). The WEB is insulated with solid silica aerogel, coated with low emissivity paints, and resistively heated under computer control during the day. This design allows the WEB to maintain components between -40degC and +40degC during a Martian sol.

The computer is provided by an integrated set of computing and power distribution electronics. The computer is an 80C85 rated at 100Kips which uses, in a 16 Kbyte page swapping fashion, 176Kbytes of PROM and 576 Kbytes of RAM. The computer performs I/O to some 90 sensors, channels and services such devices as the cameras, modem, motors and experiment electronics.

Vehicle motion control is accomplished through the on/off switching of the drive or steering motors. An average of motor encoder (drive) or potentiometer (steering) readings is used by the computer to determine when to switch off the

motors. When motors are off, the computer conducts a proximity and hazard detection function, using its laser stripping and carom system to determine the presence of obstacles in its path. The vehicle is steered autonomously to avoid obstacles but continues to achieve the commanded goal location. While the vehicle is stopped, the computer also updates its measurement of distance traveled and heading using the averaged values derived from the motor encoders and an on-board gyro.

Command and telemetry is provided by radio modems on the rover and lander. During the day, the rover regularly requests transmission of any commands sent from earth and stored on the lander. When commands are not available, the rover transmits any telemetry to the lander collected during the last interval between communication sessions. Telemetry received by the lander is stored and forwarded to the Earth.

Communication between the lander and Earth is provided twice each sol for two hours during each period. The command and telemetry functions of the rover are designed to work within these communication constraints. Commands are generally designed at a 'high-level' (for example, 'Go to waypoint', where a waypoint is a coordinate in the terrain referenced to the location of the lander) and are collected into a sequence for execution by the rover. The sequence is sufficient to carry out the mission functions of the rover on the given sol of issuance.

Commands for the rover are generated and analysis of telemetry is performed at the rover control station, a silicon graphics workstation which is a part of the MPF ground control operation. At the end of each sol of rover traverse, the camera system on the lander takes a stereo image of the vehicle in the terrain. These images, portions of a terrain panorama, and supporting images from the rover cameras are displayed at the control station. The operator is able to designate points in the terrain on these displayed images. These points serve as goal locations for rover traverses. In addition, the operator can use a model of the vehicle which, when overlaid on the image of the vehicle, measures location and heading. This information is transferred into a command file to

be sent **10** the rover on the next **sol** to correct any navigation errors **and** **command** rover traverse

## IMPLEMENTATION APPROACH

The MFEX **has** been implemented by a small **team** of engineers (**32 at peak staffing**) who at the outset planned the development within the constraints of the \$25M cost cap<sup>1</sup>. As such, the **early** focus of the effort **was** the development of a system design, a baseline of functionality of the vehicle which was used for costing the approach. **A few basic** functions were recognized as required for the mission:

- on-board navigation and knowledge of location from the lander
- hazard detection **and** **avoidance**
- mobility suited for **a** terrain of sand with many small (under 10cm) rocks and few large (greater than 1 m) **rocks**
- traverse plan developed from images displayed at a ground control workstation

These functions were developed as prototypes in the **NASA OSA-7** rover technology program through the 'Rocky' series of vehicle developments<sup>1</sup>.

With the FY92 vehicle (Rocky 4) as a **[ethnology** baseline, the team developed a cost estimate for the implementation. Several components of the eventual flight vehicle were recognized as technology challenges:

- motors** and **gears** which would operate at -80degC and survive to +110degC
- thermal design (especially the WTB) which would protect sensitive electronics to be maintained within  $\pm 40$ degC range
- cameras which could be produced cheaply and support the hazard detection system
- communication equipment which would operate with **a** free-ranging rover
- batteries which would backup a solar panel subject to **a variety of** shadowing and ill conditions
- on-board computing which would process the sensors; execute the basic driving, navigation and hazard avoidance functions of the vehicle; and **support** the command and telemetry requirements.

In addition, the components as well as the integrated vehicle must be shown qualified for the environments of the **mission** (e.g., launch within the MPL lander, 7 m on the cruise to Mars,

landing on Mars, operation in the Mars environment).

**To** accomplish this challenge the team adopted a 'rapid prototyping' approach to the implementation. Since in many instances flight qualified components were either **100** expensive or unavailable, commercial or mil-spec standard components were identified and plans to qualify through a test and selection **process** initiated. **This** was done for the case of the **motors** and gearboxes, the cameras, the **radio** modems and many electronic components for the **rover**. In cases in which there were no flight **qualified** models for the development, **as for example** the thermal design of the WTB, engineering models were developed and evaluation conducted early in the program. Finally, to **facilitate** software development and electronic component integration, a Rocky vehicle **was** delivered from the rover technology program at the start of the project and maintained as a testbed **throughout** development.

In the following sections examples of this approach are presented.

## Actuators

**The** mobility capability of the MFEX rover is a function of the rocker-bogie and 'all-wheel drive' design. Ten motors are required: one for each of **6** wheels and 4, one for each front **and** back wheel steering element. Each motor must survive the Mars **Silt** race environment, with night-time temperatures reaching +110degC, **and** **operate** during early morning **conditions**, when temperatures are not warmer than -80degC. When surveying the industry for **motors** which might satisfy these requirements, **motors** designed for space flight **application** are nominally brushless with integrated electronics, not suited for operation at these temperatures. Wire routing to move the electronics from the wheel to inside the rover's WTB would **be** cumbersome (many wires crossing moving components) and be the source of a heat leak. This dictated looking at an alternate technology, brush motors, which **is** generally **available** for commercial not space flight applications. After a survey of commercial motor vendors, the Maxon motor was chosen, with its superior torque versus mass performance and a commutation

scheme **suited** for the prevention of a clog, an **issue** for the 8 Torr atmosphere at the Martian surface.

The actuators for the MFEEX rover also require a gearing design **which** transfers many turns of the shaft of the motor into torque to move kilograms **of mass**. Again the MFEEX project turned to the commercial market to procure a gear box for the **application**. Early development testing of this gear train and **motor assembly** revealed freeze-up and high breakaway torque required to start the actuator at temperature. MFEEX engineers worked **closely** with Maxon to encapsulate the capacitors to improve the power-use performance at temperature **of the motors**. In addition, this testing **helped** MFEEX engineers identify and remove **greases** and friction from the gearbox which were sources of the freeze-up. The result is an actuator which operates at Mars environment, draws less than .5 Watt maximum output, and **has** shown no degradation after 8 km of lifetime tests at temperature.

#### Modems

The MFEEX rover gathers **data** during its mission and communicates **to a** lander for 'store and forward' service **to the earth**. This free ranging characteristic of a planetary rover makes wireless communication essential. However, space flight **examples of such relay communications** (shuttle 10-11111SS, probe-to-Galileo) involve high powered (**several** 100W of radiated power) **systems** designed for many kilometers of signal relay. The MFEEX rover is **planned** to range from the lander only 10's of meters and in prototype demonstrations **was** capable of acceptable communication through low power (under 2W) UHF **modems**. When surveying the industry, no space flight qualified equivalent systems **was** available and only a few mil-spec radio modes were identified **as applicable, but at** a prohibitive cost. The MFEEX project turned to the commercial market **and**, in particular, one of the largest commercial manufacturers of wireless communication devices, **Motorola**, for a device which would satisfy its data transfer needs.

The RNET modem was chosen both for its low power and rugged packaging, most nearly suited for the mission **environment**. Yet, this radio modem would need to satisfy mission

requirements (operate from -40degC to +140cdeg, in the WTB), operate under radiation conditions (where latch-up will not occur for a LET below 30), and survive a derived **dynamic** environment associated with a 50g landing **load**. JPL and Motorola engineers worked together to characterize performance at temperature **and** under radiation, and adapt the radio modem **and its** supporting electronics **to function under** the required conditions.

In early testing, latch-up **of the** modem would occur at a LET under 25. However, **the latch-up** was non-destructive: the modem **was** left in a latch up state for over 1 hr > power cycled, then shown to work properly thereafter. The adaptation **of** the modem then involved the addition **of** circuitry and software **control to** detect and then correct through a **power cycle of** the device when a latch-up **occurs**.

Given that **the** manufacturer's rating **of the** modem **was** for operation between of -30degC **and** +45degC, **the** MFEEX project planned to test the modems at lower temperatures and select those which would operate best through the -40degC temperature range for the WTB. This testing and selection process resulted in **devices** which worked acceptably (i. e., bit error rates less than 10<sup>-5</sup>) throughout the temperature **range** as determined through communication **to an** external, reference modem maintained at room temperature. In characterization tests of pairs of modems where temperatures can vary (**the** condition of the MFEEX mission where a modem on the lander will be at a temperature distinct from that of a modem on the rover), performance degraded: bit error rates of greater than 10<sup>-3</sup> were observed. The cause of the problem was frequency drift in the crystal **oscillator (anti** related parts **of** the circuitry) **of the** modem at temperatures below -20degC. An **external, temperature controlled crystal oscillator** is under consideration for replacement **of the crystal oscillator** packaged with the RNET modem. This replacement would need to **occur after** the delivery of the MFEEX rover to the MPF flight system and be part of a retrofit, prior to launch. Alternately, a heating scheme **has been evaluated** and shown to improve the performance **of the** modems. The modem is equipped with a heater which is powered on whenever **the** temperature in the WTB is below -10degC and communication between the rover and lander is required.

### Insulation of the WEB

The requirements for the thermal design of the WEB were to maintain electronics within  $\pm 40^{\circ}\text{C}$  temperature range in the presence of two distinct thermal environments: operations on Earth during test, on the launch pad in configuration with the MPF lander, cruise, attached to the lander **op cm** delivery to **Mrs Mars** surface exploration. In addition, the **WEB 1**, was required to meet a mass target of under 2 kg **satisfy** the 60cm x 48cm footprint of the vehicle and **satisfy a heat leak** requirement of under 2W.

Several insulation techniques were considered for the application: Owens-Corning **Aura™** vacuum jacketed **fiber** insulation, polyurethane foam, opacified aerogel **powder** encapsulated in Norex honeycomb core, and **solid silica** aerogel in sheet and **spar** structural design. The nonrigidized vacuum bottle concept of Owens-Corning **Aura™** essentially uses thin metal sheets sealed around evacuated fiber glass insulation. Although acceptably low in conductivity, the edge effects of the individual **small panels** were impractical given the need for additional mass to support the design. The polyurethane foam **was bulky** and the required amount for the thermal design could not be **satisfied** within the volume and mass constraints of the rover. The design developed using the opacified aerogel powder in the Norex honeycomb **had acceptable** thermal performance characteristics. However, two problems emerged when a WEB of this design was built. The opacified aluminum added to the aerogel powder available commercially resulted in a bulk density of 160mg/cc. The resulting insulation did not meet the mass requirement. In addition, initial dynamic testing of the WEB with this design showed a tendency for separation of the material resulting in 'cold spots'. Although this was most prevalent in weightless conditions which could be addressed by other means during cruise another design was considered.

The solid **silica** aerogel **was** selected as the **insulation** material for the MFEX rover due to **positive** experimental and analytical results for thermal conductivity and bulk densities. The manufacture of 20mg/cc **which** offered promise of meeting the mass requirement. This selection

was not without its own problems, since the material at this density was produced in an autoclave unique to a JPL technology program and only in quantities sufficient for use in a proposed sensor program. **Also this** decision was reached only after the above **approaches** had been rejected; the approaches used in developing the cost estimate for the project. The **time** was 18 months (3/94) into the project and a WEB of **all** acceptable design was due for initial integration with other rover components within 9 months (12/94). A significant design and development effort by MFEX engineers and technologists ensued, resulting in the **completion** of a WEB for evaluation and test (1/95). The success of the first thermal environment and dynamics **test kept** MFEX rover integration on schedule but at the cost of the first significant allocation of reserves.

### Software Development Model

Prior to the initiation of the MFEX **project** a Rocky vehicle had been demonstrated **performing** a science mission resembling the initially planned investigations for the MPF **mission**. The success of this demonstration **established a** technology baseline for the MFEX project. But also resulted in the delivery of the Rocky vehicle (Rocky 4) to the project.

Rocky 4.1 was the Rocky vehicle stripped to the bare chassis for mobility testing in sand and lunar simulant. Motors and **mechanisms** which were close analogs of those **considered** for the flight rover were added for these tests. Rocky 4.1 was then upgraded with a wire-wrap computing breadboard, the gyro and accelerometers selected for the flight rover, commercial cameras and laser stripers, and the RNET radio modem. This vehicle (Rocky 4.?) became the testbed for software development. The basic **navigation** and hazard avoidance algorithms, **motor** and vehicle control strategies, the communication **protocol**, command and telemetry **formats**, and the memory management and processing architecture of the MFEX rover was developed on this testbed. A version of this software **was** running on Rocky 4.1 by the end of the first year of the project and evaluations in a sandbox were conducted.

When the first Maxon **motors** and gearboxes **intended** for the MFEX rover were available, Rocky **was** retrofitted becoming Rocky 4.3. Software development **cent** inued with upgraded of the vehicle control and monitoring algorithms. In addition, Rocky 4.3 supported the first end-to-end data system test conducted by the **MP1 EX** project. In this test, communication between Rocky, a testbed **version** of **tbc** MP1 **hi: hi** computer and the **first** version of the ground data system established the functionality of this part of the **mission data flow** and allowed interface agreements **among** the **various** systems to be **involved** to be verified. Rocky 4.4 contained the first assembled cameras **and** lasers of the **MFEX** rover **design** and supported the test of the engineering **model** of the APXS deployment mechanism.

The first prototype computer and power distribution boards **for** the MFEX rover **was** developed in a wire wrapped brassboard configuration. When configured with the rest of **tbc** Rocky vehicle, Ibis became Rocky 4.5. "The **mass** and volume of this brassboard set of electronics made **Rocky** 4.5 the first non-mobile vehicle in the **Rocky** series. However, as a benchtop testbed, the **interfaces** to flight versions of Component electronics and the software **management** of the MFEX rover sensors **was** verified with Rocky 4.5.

The final **prototype** in this series **was** Rocky 4.6 with a discrete **wired**, printed circuit board version of the MFEX rover electronics. All but a few of the components on these circuit boards were flight parts. The construction of these boards tested the **production** process for the eventual flight **electronics boards** for the **MP1 EX** rover and were **tbc** functional and physically equivalent of these boards. While the evaluation **model** of **tbc** MFEX rover **was** being constructed (the System Integration Model rover or SIM), Rocky 4.6 **was** the testbed for the flight software. The timing and interface protocols to all electronics were developed and tested. The structure, size and data management employed by the flight software **was** verified on Rocky 4.6 and this vehicle participated in **tbc** final phase of the **end-to-end** information system tests prior to the initiation of **tbc** Assembly, Test and Launch Operations (ATLO) for the MP1 project.

Rocky serves as the best example of the 'rapid prototype' process **used** by the MFEX project. Throughout the entire course of **tbc** project a 'version' of the eventual flight vehicle **was** available for software **development**, system **test** and evaluation purposes.

## SYSTEM INTEGRATION MODEL (SIM)

The final steps of the implementation process used by the **MP1 EX** project **was** the development in tandem of two rover vehicles: the 'System Integration Model' or SIM and the Flight Unit Rover or FUR.

"The SIM **was** intended as the engineering or evaluation model of the eventual MFEX rover. All assembly procedures, **environment** tests, functional tests, fit checks, **cleaning** procedures and ground support equipment **development** were first checked on the SIM before being applied to the FUR. Since the SIM and FUR were constructed to the same set of blueprints, the test experience of the SIM **was** a direct analog to the eventual performance of the FUR under similar test conditions. The usual 'qualification level' test conditions were applied to the SIM: temperature extremes  $\pm 15^{\circ}\text{C}$  beyond the expected nominal conditions, static load conditions 3 sigma above predicts, dynamic loads a factor of 2 above those established for flight acceptance, etc. All but one test **was** passed by the SIM, giving confidence [bat the FUR when exposed to 'flight acceptance levels' of the same tests would pass without a problem.

The one test case failure occurred during the centrifuge test of the SIM. In the tic-down configuration of the rover to the MP1 lander petal wheel cleats mesh to similar material on the mounting hardware on the petal. Due to wear of the cleat through the extensive series of functional tests (the centrifuge **was** the last environment test of the SIM), cleat bonds failed and a wheel released on the final axis of the centrifuge test, rotating around the wheel cages to strike and damage the SIM solar panel. Ibis led to a redesign of the wheel cleats and **tbc** introduction of rivets to augment the cleat bonds. The wheel of this revised design **was** tested with the FUR in a centrifuge test at the flight acceptance levels and the FUR passed this test without incident. The SIM with **tbc** revised

wheel cleats will be **tested** again at the qualification levels for **static** loads.

With the assembly, **test** and delivery of the FUR to the MPF project **completed**, the SIM has become the testbed supporting software parameters tuning, operations planning and personnel training for the operation phase of the Pathfinder mission. As a part of these activities, the SIM will undergo field testing in outdoor test facilities at JPL and elsewhere demonstrating the robustness of the mobility, navigation and hazard avoidance systems.

As testament to the benefit of this implementation approach, the FUR was integrated with the MPF lander without a problem, satisfying all mechanical and electrical interface requirements. The software delivered with the FUR has been shown to work with the MPF lander flight computer software and ground system. All can be attributed to the incremental test and development approach employed by MFEX.

## SUMMARY

The 'rapid prototyping' approach of the MFEX project has proved successful in leading to the delivery of the MFEX rover to the MPF flight system. As can be seen in Fig. 2, the cost incurred by the project at time of this delivery is roughly two-thirds of the available resources.

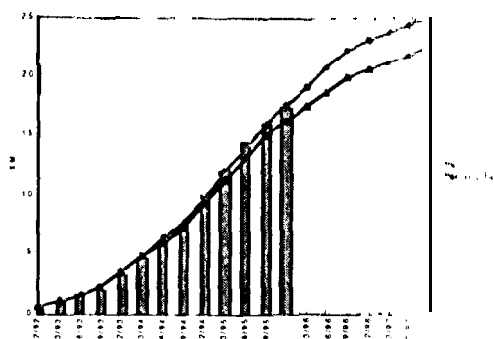


Fig. 2 MFEX Cost Performance

The implementation plan developed during the first year of the project and presented at the MFEX project Design, Implementation and Cost Review (DICR) has proved remarkably accurate. The small reserve of the MFEX project (less than \$3M of the \$25M cost cap) and only available

after the first year of the project has been sufficient to address problems in the development and test program conducted by the project. As the first flight microrover development, the MFEX project has shown that a technology development can be taken through implementation in the span of 40 months using the approach described herein. The small MFEX engineering staff looks forward to the launch and operation phase of the mission.

## ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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